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THE LAKESHORE CAPACITY STUDY. PART 1:

A TEST OF THE EFFECTS OF SHORELINE DEVELOPMENT ON THE TROPHIC STATUS OF LAKES

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THE LAKESHORE CAPACITY STUDY. PART I:

A TEST OF THE EFFECTS OF SHORELINE DEVELOPMENT ON THE TROPHIC STATUS OF LAKES

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ABSTRACT

A simple mass balance model combined with detailed hydrologic and mass balance measurements yielded accurate predictions of TP concentration in lakes with no shoreline development. On the other hand, the model based on natural TP loads only predicted lower than observed TP concentrations in 4 developed lakes; however, in 3 of the 4, the predictions and observations were virtually identical if the potential TP contribution from shoreline development was included in the budgets. In the exception, Harp Lake, the only one of the 4 with thick deposits of till/soil, the predicted and observed trophic status matched if about a third of the potential input from shoreline development reached the lake. This suggests that in this case the till/soil was effective in retaining a significant portion of the TP transported in septic systems.

Lakes with oxic and anoxic hypolimnia were differentiated by using different apparent settling velocities in the mass balance model. A lower setting velocity in those with anoxic hypolimnia is consistent with TP release from the sediments in these conditions.

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Table 6. The total loading of TP (L_T) from external (L_{EXT}), internal (L_{INT}), natural ($L_{NAT} = L_{EXT} + L_{INT}$) and anthropogenic ($L_A$) sources (mg/m^2/yr), the measured areal water load (q_s in m/yr), the predicted fractional retention of TP (R_p) and the measured ($[TP]_{meas}$) and predicted total phosphorus concentration during the ice-free season (mg/m^3) from natural only ($[TP]^{NAT}_{pred}$) or all TP inputs ($[TP]^{T}_{pred}$) for the moderately developed lakes. All data are averages for 12 years.

Table 7. The total loading of TP (L_T) from external (L_{EXT}), internal (L_{INT}), natural ($L_{NAT} = L_{EXT} + L_{INT}$) and anthropogenic ($L_A$) sources (mg/m^2/yr), the measured areal water load (q_s in m/yr), the predicted fractional retention of TP (R_p) and the measured ($[TP]_{meas}$) and predicted ($[TP]_{pred}$) total

phosphorus concentration during the ice-free season (mg/m^3) from natural only ($[TP]^{NAT}_{pred}$) or all TP inputs ($[TP]^{T}_{pred}$) in the extensively developed lakes. All data are averages for 12 years.

INTRODUCTION

The means to predict the potential impact of proposed shoreline development on lake water quality must be available so that rational decisions can be made. Consequently, over the past 2 decades quantitative relationships have been developed for the prediction of specific water quality parameters such as chlorophyll a concentration (Dillon and Rigler 1974, Prepas and Trew 1983, Riley and Prepas 1985, Ostrofsky and Rigler 1987, Molot and Dillon 1991), algal biomass (Nicholls and Dillon 1978, Kalff and Knoechel 1978, Schindler *et al.* 1978, Prepas 1983, Chowfraser 1991), water clarity expressed as Secchi disc depth (Canfield and Hodgson 1983, Ostrofsky and Rigler 1987) and the rate of loss of oxygen from the hypolimnia of lakes (Cornett and Rigler 1979, Welch and Perkins 1979, Charlton 1980).

Since phosphorus has been found to be the nutrient most often limiting primary production and algal standing stock in north temperate lakes (Schindler *et al.* 1971, Fuhs *et al.* 1972, Schindler 1977), relationships between total phosphorus (TP) and trophic status parameters have been the most common (e.g., Nicholls and Dillon 1978, Prepas and Trew 1983, Riley and Prepas 1985, Stockner and Shortreed 1985, Shortreed and Stockner 1986, Ostrofsky and Rigler 1987). Dillon and Rigler (1975) developed a conceptual model for the assessment of the effects of shoreline development on chlorophyll a concentration (Figure 1). The basis for this and other trophic status models is a mass balance model for prediction of TP concentration in the lakewater combined with TP-trophic indicator relationships, the latter often empirical in origin.

The Dillon and Rigler (1975) model included both natural inputs of TP (from the catchment, affected by its geology and land use), inputs via atmospheric deposition directly onto the lake's surface and anthropogenic inputs of TP from shoreline development and sewage disposal systems. However, the anthropogenic inputs of TP in the model were derived from the largely untested assumption that all of the TP going into these private waste disposal systems (primarily septic tanks with tile beds) ultimately reaches the associated lake. While this is clearly a conservative assumption with respect to lake water quality, it requires further testing.

In 1975, the Ontario Ministry of Municipal Affairs in cooperation with the Ontario Ministries of the Environment and Natural Resources initiated the Lakeshore Capacity Study. The purpose of the study was to quantify the effects of lakeshore development on inland lakes. In the original study design, 5 factors were considered in assessing the impact of shoreline development (effects on fisheries, wildlife, human health, lake water quality and socioeconomic factors); however, the work described in this paper concerns only lake water quality, specifically trophic status.

The purpose of this paper is to report on our test of the assumption that all of the TP from private sewage disposal systems ultimately enters the lake. In the subsequent paper, we re-evaluate the Dillon and Rigler (1975) conceptual model and revise and recalculate the trophic status relationships specifically for lakes in the narrow trophic range typically found in the Precambrian portion of Ontario.

APPROACH

The ability of natural soil or till deposits in the catchments of lakes to assimilate or retain TP which is released from private sewage disposal systems is difficult to quantify, in part because of their heterogeneity, and, in part, because of the relatively long time required for the nutrient to reach steady-state with the soil. In most instances, it is difficult even to assess the quantity of soil or till interacting with the effluent discharged by the sewage systems. For these reasons, we did not rely on following potential changes in trophic status in an undeveloped lake following development. Therefore, in order to test the assumption that all of the TP discharged by private sewage systems enters the lake, we utilized an indirect approach. We compared the nutrient regimes of lakes with shoreline development to those with no development. Six lakes were selected based on their degree of shoreline development. Two of the lakes had little or no development (Red Chalk and Jerry), 2 had some development (Chub and Blue Chalk) and 2 were extensively developed (Dickie and Harp). In the cases of the latter 4 lakes, the shoreline development had existed for a substantial length of time, the ages of the cottages averaging more than 30 years. This criterion was included so that potential interactions of septic system effluent with the till/soil could have had considerable time to reach steady-state conditions. Preliminary surveys of the lakes in conjunction with estimates of relative magnitude of TP sources (Dillon and Rigler 1975) indicated that potential anthropogenic inputs could contribute about 26, 27, 54 and 61% percent of the TP loading to Chub, Blue Chalk, Dickie and Harp Lakes, respectively (Table 1).

These estimates, which were based on published nutrient export and nutrient budget models, were used only for the lake selection process. All components of the mass balances were subsequently measured as accurately as possible.

First, the concentrations and all measurable inputs of TP to both the undeveloped and the developed lakes were determined. Next, we used a modified version of the Dillon and Rigler (1975) model to see if we could accurately predict the TP concentrations in the undeveloped lakes. Finally, we tested if the input of TP from natural sources could explain the observed TP concentrations in the lakewaters of the developed lakes, or if it was necessary to include potential TP input from anthropogenic sources to explain the observed TP concentrations.

To predict TP concentrations in the lakes we used the mass balance model (Vollenweider 1969; Figure 2) described by equation (1):

$$d\,[TP]/dt = J_T/V - Q[TP]_{OUT} - \sigma[TP] \qquad (1)$$

where [TP] is the concentration of TP in the lake (mg/m^3), J_T is the total supply of TP to the lake (mg/yr) and includes the natural supply of TP from external sources (J_{EXT}), the internal supply from the sediments (J_{INT}) and the anthropogenic supply (J_A) from private sewage disposal systems, Q is the volume of water flowing out of lake (m^3/yr), V is the lake

volume (m^3), $[TP]_{OUT}$ is the concentration of TP in the lake outflow (mg/m^3) and σ is the sedimentation rate constant (1/yr).

Although in a uniformly and instantaneously mixed system [TP] is equal to $[TP]_{OUT}$, we have observed that the TP concentrations in most lake outflows are not equal to the concentration in the lake (Dillon et al. 1986). We used the empirical relationships based on long-term observations for a number of lakes in central Ontario:

$$[TP]_{OUT} = 0.956\ [TP] \quad (2)$$

Therefore, at steady state equation (1) reduces to:

$$[TP] = L_T(1-R_p)/(0.956\ q_s) \quad (3)$$

Where L_T is the total areal loading rate of TP (i.e., J_T/A_o in $mg/m^2/yr$ where A_o = lake surface area), R_p is the fraction of the total input of TP lost to the sediments and q_s is the areal water load (i.e., Q/A_o in m/yr).

We used $[TP] = [TP]_{if}$, i.e., treated the annual average TP concentration and the mean TP concentration in the lake during the ice-free period (mg/m^3) as equivalent.

The retention of TP, R_p was calculated as:

$$R_p = 12.4/(12.4 + q_s) \tag{4}$$

Equation (4) was developed by Kirchner and Dillon (1975) from empirical calibration of the relation between settling velocity, v (in m/yr) and areal water load, q_s using data collected from oligotrophic, Precambrian Shield lakes with hypolimnia that were oxic throughout the period of thermal stratification. That is:

$$R_p = v/(v + q_s) \tag{5}$$

STUDY AREA

The six study lakes are located near the southern boundary of the Canadian Precambrian Shield in the District of Muskoka or in Haliburton County, south-central Ontario. The lakes are similar in size, with surface areas ranging between 34 and 94 ha, mean depths of 5 to 14 m and maximum depths of 12 to 38 m (Table 2). Most are clear (colour = 5 - 12 Hazen units) with the exception of Dickie and Chub Lakes ($\approx$48 Hazen units) and most have relatively low ionic strengths (conductivity = 29 - 38 uS/cm), although 2 of the lakes (Jerry and Harp) have slightly higher conductivities and cation concentrations (Table 1). This is a consequence of the fact that the glacial till in the catchment of these lakes is substantially thicker (as much as 10 to 15 m) than in the other 4 lakes where surficial deposits are generally less than 1 m. All of the lakes except Red Chalk have single morphometric

basins; Red Chalk Lake has 2 basins separated by a narrow, shallow channel.

A summary of the physical and chemical characteristics of the study lakes and their watersheds is given in Table 2. More complete descriptions are outlined in Rustad *et al.* (1986), Reid *et al.* (1987), and Dillon *et al.* (1986, 1991).

METHODS

a. Hydrologic Budgets

Details of the methods used for measuring the hydrologic budgets of the lakes are described in Scheider *et al.* (1983), Locke and Scott (1986) and Dillon *et al.* (1986). Briefly, the water levels of all the major inflows (22 in total) and the outflows for each lake were monitored continuously using water level recorders. Weirs and/or flumes were installed on each stream so that instantaneous discharge measurements could be made. Two of the lakes, Blue Chalk and Chub, had anoxic hypolimnia each year, while Harp, Jerry and Dickie remained oxic. One basin of Red Chalk Lake (Main) remained oxic while the smaller basin's hypolimnion was anoxic each year. Water levels were converted to continuous discharge using a stage-discharge relationship for each stream (Scheider *et al.* 1983). These relationships typically were based on 200-400 instantaneous measurements of discharge.

Precipitation depth was measured at 4 (after 1980) or 8 (prior to 1980) meteorological stations within the study area. Evaporation was calculated as the residual term in the energy balance equation for each lake while lake storage was estimated from changes in lake levels.

It was assumed (and later verified) that there were no significant groundwater inputs to or outputs from the lakes.

Water balances reported here encompass 12 hydrologic years (i.e., June 1, 1977 - May 31, 1989) for all the lakes except Jerry Lake, where data for only 3 years (i.e., June 1, 1977 - May 31, 1980) are reported. The balances were evaluated by comparing the ratio of the difference from ΔW:

$$\Delta W = \Sigma Q_i + P - E_V - Q_O \pm \Delta S \qquad (6)$$

to the total loss from the lake ($Q_O + E_V \pm \Delta S$), where ΣQ_i is the inflow volume of all sources in the catchment, P is precipitation directly on the lake surface, E_V is evaporation from the lake, ΔS is the change in storage and Q_O is the outflow volume.

b. Sampling for Total Phosphorus

All the streams were sampled for TP analysis at least once every two weeks during winter, as frequently as possible (>once/week) during spring melt and weekly during the remainder of the year from 1977 to 1989. Beginning in 1982, the inflows to Dickie and Harp Lakes were sampled daily during spring melt and 3 times per week during the rest of the year. All samples were collected in Nalgene bottles and then filtered through 102 μm Nitex mesh into autoclaved and pre-rinsed 50 mL auto analyzer tubes.

Wet and dry deposition of phosphorus was measured using bulk precipitation collectors (see

Dillon *et al.* 1988 for details). Samples were removed from the collectors when there was sufficient volume for chemical analysis. Thus, collection periods ranged from 1 day (spring) to 40 days (winter), with most samples being collected weekly. All samples were filtered through 76 μm (1976-1982) or 102 μm (1982-1989) Nitex mesh to remove coarse particulate material.

For the five single basin lakes, lake water samples were collected at the deepest part of the lake using a peristaltic pump whereas the 2 basins of Red Chalk Lake (Main basin and East basin) were sampled separately. For TP samples, aliquots of water, proportional to the volume of the stratum represented, were collected at 2-m depth intervals to lake bottom, and then combined to give a single volume-weighted, composite sample. During stratification, composite samples from each of the epi-, meta-, and hypolimnia were collected, whereas under conditions of thermal homogeneity (including winter), waters from all depths were combined to give a single, volume-weighted, composite sample representative of the entire lake (or basin in the case of Red Chalk Lake). All the lake samples were filtered through 250 μm mesh to remove coarse particulate material; subsequent analysis indicated that the >250 μm component represented a small (almost always <5%) proportion of the TP in the water column. Lakes were sampled on a weekly basis during the ice-free period and monthly during the winter from 1977 to 1989.

The analytical method for TP is described in detail in MOE (1983).

c. Phosphorus Mass Balances

The method for calculating the supply of TP from external sources (i.e., J_{EXT} from precipitation and from catchment inputs), as well as the outflow of phosphorus (J_{OUT}) from the lakes, is described in Scheider *et al.* (1979). Briefly, the daily deposition of TP from precipitation for each bulk collector was calculated by multiplying the TP concentration in the sample by the cumulative precipitation depth for the sampling period and then dividing by the number of days in the period. TP inputs (in mg/yr) from the gauged inflows and TP outputs via outflow were determined by multiplying the TP concentration (measured during the midpoint of the time period) by the total discharge (Q) for that time period. Inputs of TP to the lake from ungauged portions of the watersheds (range in area as a proportion of the total catchment area is 18.3% in Red Chalk Lake to 80.7% in Blue Chalk Lake) were estimated by pro-rating the gross export (i.e., output/watershed area) from the hydrologically gauged subcatchments in each lake's catchment.

Internal supply of TP (J_{INT} in mg/yr) from the lakes' sediments was calculated (Nurnberg 1984) as:

$$J_{INT} = \Delta[TP]_{hypo} \cdot V_{hypo} + \Delta[TP]_{ic} \cdot V \qquad (7)$$

where $\Delta[TP]_{ic}$ and $\Delta[TP]_{hypo}$ are the changes in the TP concentrations in the whole lake during the ice-covered period and in the hypolimnion during summer stratification,

respectively ($mg/m^3/yr$), and V and V_{hypo} are the lake volumes and hypolimnetic volumes, respectively (m^3).

Potential anthropogenic inputs of TP (L_A) from private sewage disposal systems (including septic tank/tile field systems, leaching pits, aerobic systems and holding tanks) were estimated using the equation:

$$L_A = 0.80\ (1-f_h)N \cdot 0.75/A_o \tag{8}$$

where 0.80 kg TP/capita/yr is the potential input of TP from sewage disposal systems, assuming that the facility is 0% efficient at removing TP (except for holding tanks which are assumed to be 100% efficient), N is the number of cottages, and 0.75 capita yr/yr/unit is the cottage usage (Dillon *et al.* 1986). The quantification of the # of cottage units on the lake and the type of sewage disposal facility including the fraction of the units using holding tanks, f_h was determined from surveys conducted by the Ontario Ministry of Housing from 1976-1978 which have been updated recently (P. Dillon, unpubl. data).

RESULTS AND DISCUSSION

a. Hydrologic Budgets

The mean discrepancies in the hydrologic budgets, expressed as the ratio of the difference between total input and total loss of water from the lake to the total loss of water ranged

between 2.7 and +5.1% (n = 3 years for Jerry Lake and n = 12 years for the other lakes) for the study lakes (Table 3). The lake with the greatest imbalance was Blue Chalk Lake, the one with the highest proportion of its catchment not gauged. Even in this case, however, the imbalance was only 5.1%. While the observed differences (average of all lakes = +2.7%) could represent minor measurement errors, it is evident that there are no major components missing from the water balances. Thus, the assumption that groundwater inputs are negligible appears to be valid. The mean of the absolute difference was slightly higher (range 3.2-6.7%, average 4.6%), but was still very low. The average replenishment time for these lakes ranged from 1.2 yr (Jerry Lake) to 5.3 yr (Blue Chalk Lake).

b. Phosphorus Mass Balances

A summary of the parameters needed for the mass balance calculations (equation (3)) and the TP concentrations which were measured in the six study lakes are given in Tables 4 to 7. Atmospheric deposition was a significant source of TP to the study lakes, in some cases (Plastic Lake, Blue Chalk Lake) contributing well over half the natural TP load. The relative importance of atmospheric deposition and runoff from the catchment are discussed in detail in Dillon *et al.* (1992). For all the lakes, internal sources of TP were small (maximum = 26 $mg/m^2/yr$ for Chub Lake) with the internal input being generally less than 10% of the total phosphorus load (22% for Chub Lake). The predicted retention of TP by the lakes' sediments, R_p ranged between 0.56 and 0.82 while the areal water load, q, varied by about an order of magnitude, ranging between 1.61 m/yr in Blue Chalk Lake and 10 m/yr in Jerry Lake. Potential anthropogenic loadings of TP from septic tanks (estimated

from equation (8) and then divided by lake area), ranged between 0 (Jerry Lake) and 117 $mg/m^2/yr$ (Harp Lake), and thus may have contributed as much as 58% of the total phosphorus input. The relative anthropogenic loadings differed from the pre-study estimates shown in Table 1 because of better information regarding cottage numbers and usage and because they were based on actual measured TP budgets rather than estimates.

i) Red Chalk and Jerry Lakes

For Jerry Lake, which has no shoreline development, the predicted and observed TP concentrations (Table 4) were almost identical (8.7 mg/m^3 and 8.6 mg/m^3, respectively). For Red Chalk Lake, which has virtually no shoreline development, the predicted TP concentration was 4.6 mg/m^3 (4.7 if potential cottage input is included), which is within 10% of the measured concentration of 5.1 mg/m^3. Despite this good agreement, we believed that the small eastern basin of Red Chalk Lake was acting very differently than the main basin with respect to TP fluxes. This was based on the observation that the measured TP concentration in the eastern basin was higher (7.8 mg/m^3 vs. 4.9 mg/m^3); the differences were especially apparent in the hypolimnetic values which exceeded 30 mg/m^3 in the eastern basin, but were not elevated above 8 mg/m^3 in the hypoliminion of the main basin. To test this hypothesis, we constructed separate hydrologic and TP mass balances for each basin of Red Chalk Lake. The results (Table 5) indicate that for the main basin of the lake, the predicted and observed TP concentrations during the ice-free season are very close (4.6 mg/m^3 and 4.9 mg/m^3, respectively). However, for the East Basin of the lake, the predicted $[TP]_{if}$ (6.4 mg/m^3) is substantially lower than the observed concentration (7.8 mg/m^3). Thus, the TP mass balance model outlined in equation (3) provided an accurate prediction of

$[TP]_{if}$ for Jerry and Red Chalk (Main) Lakes, but not for the east basin of Red Chalk Lake.

The difference between these lakes is that the hypolimnia of both Jerry and Red Chalk (Main) Lakes were oxic during the period of summer stratification, whereas the hypolimnion of Red Chalk (East) Lake was not (Reid *et al.* 1983, Girard and Reid 1991e,f), and as a consequence of this, the TP concentration in the hypolimnion of the East Basin of Red Chalk Lake was much greater than in the epilimnion. This was not the case in either Jerry or Red Chalk (Main) Lake.

As a result of these observations and those of others (Reckhow 1977), we decided that an alternate formulation of equation (4) was required for lakes with anoxic hypolimnia. In these lakes, increased TP concentrations in the hypolimnion indicate either release of TP from the sediments or less efficient removal of TP from the water column. While these two possibilities are indistinguishable, they can be described mathematically by a net decrease in the settling velocity, v (equation (5)). Since in the East Basin of Red Chalk Lake there is no anthropogenic input of TP from lakeshore development, equation (5) can be recalibrated simply by optimizing v (in Red Chalk Lake East Basin) so that the observed and predicted TP concentrations agree. The result of this procedure is:

$$R_p = 7.2/(7.2 + q_s) \qquad (9)$$

i.e., an apparent settling velocity of 7.2 mg/yr was used for lakes with anoxic hypolimnia as opposed to 12.4 m/yr. Equation (9) was used for the anoxic lakes (Blue Chalk and Chub)

while equation (4) was used for the oxic lakes (Dickie and Harp).

ii) Blue Chalk and Chub Lakes

For the two lakes with moderate levels of shoreline development, the TP concentrations predicted from natural TP inputs alone (i.e., excluding L_A, the potential anthropogenic input) are 70% (Blue Chalk Lake) and 93% (Chub Lake) of the measured TP concentrations (Table 6). However, if inputs from cottages (as calculated from equation (8)) are included in the calculations, then the TP concentrations predicted from equation (3) are much closer to the measured concentrations. For Chub Lake, the total predicted $[TP]_{if}$ (11.2 mg/m^3) is about 6% higher than the measured concentration (10.5 mg/m^3) while while for Blue Chalk Lake, the predicted $[TP]_{if}$ (5.8 mg/m^3) is less than 10% lower than the observed concentration (6.4 mg/m^3). These predicted results are within the range of inter-and intra-annual variability in measured values, which averaged about 10% for all lakes.

Although measurement or model error could explain the small underestimate of predicted TP concentration in Blue Chalk Lake, the information on human usage (in capita yr/yr) of the development units around the lake are the weakest data. It is possible, because of the extremely low natural load of TP (39 mg/m^2/yr), that relatively small errors in the estimate of the potential anthropogenic input could affect the predicted concentrations substantially. On the other hand, the measurement of input of TP from the catchment of Blue Chalk Lake was undoubtedly less accurate than those for the other lakes because a greater portion of the catchment was not gauged.

iii) Dickie and Harp Lakes

The predicted and observed TP concentrations in the two lakes with extensive shoreline development are given in Table 7. Dickie Lake did not have a hypolimnion in all years of study (Reid *et al.* 1983, Girard and Reid 1991d), possibly because of its shallow depth (z_{max} = 12 m) and relatively large surface area (93 ha). In a few of the 12 years, there was very weak stratification and oxygen depletion in the bottom meter, but as this represents a very small portion of the lake area (ca. 1%), the oxic model was used.

The predicted [TP] in Dickie Lake based on the oxic model and natural inputs only, is considerably less than the measured concentration (5.8 vs. 11.7 mg/m^3). However, if all of the potential input from private sewage disposal systems is included, the predicted [TP] (11.6 mg/m^3) has almost identical to the measured concentration. In the unlikely case that the anoxic model is more suitable for Dickie Lake, the predicted TP concentration (including both natural and anthropogenic inputs) was 18.0 mg/m^3, more than 50% higher than the measured concentration of 11.7 mg/m^3.

In Harp Lake, the predicted $[TP]_{if}$ excluding anthropogenic inputs was about 30% lower than the measured value of 7.5 mg/m^3. However, the inclusion of L_A resulted in the predicted TP_{if} (12.8 mg/m^3) being about 70% higher than the measured concentration. Thus, for 3 of the 4 lakes with moderate or extensive shoreline development, most or all of the TP discharged from private sewage disposal systems, appears to enter the lakes.

The reason for the difference between the results obtained for Harp Lake relative to Chub, Blue Chalk and Dickie Lakes may be related to the nature of the surficial geology of the lakes (Table 1). The surficial deposits of Chub and Dickie Lakes are composed primarily of very thin (< 1 m) till and rock outcrops (61 and 81%, respectively), while relatively thick deposits of till are found in the basins of Jerry and Harp Lakes (Jeffries and Snyder 1983). While no detailed information regarding the ability of soils to bind or retain TP was obtained in this study, it seems likely that the thicker (up to 15 m) till/soil deposits around these 2 lakes would have a greater TP binding capacity than would the thin (< 1 m) surficial deposits in the basins of the other 4 lakes. This has no impact on Jerry Lake, which is currently undeveloped. However in Harp Lake. the net effect is that all of the TP discharged from private sewage disposal systems, may not be entering the lake. By rearranging equation (3) and solving for L_T, it is evident that a loading of 119 mg/m^3 is required to obtain the measured [TP] of 7.5 mg/m^3. Since the natural loading of TP to Harp Lake is 86 mg/m^3 (Table 3), then only 33 mg/m^3 or 28% of the potential anthropogenic supply of 116.8 mg/m^3 must enter the lake to explain the observed TP concentration.

CONCLUSIONS

TP concentrations predicted using hydrologic and mass balance measurement matched measured concentrations for lakes with no shoreline development. In order that measured and predicted levels matched for lakes with shoreline development, the potential anthropogenic TP input from the development had to be included in the calculations. In

3 of 4 cases, the evidence indicated that all of the TP transported into and out of septic systems reached the lakes; in the fourth, the only one with thick (up to 15 m) till/soil around the lake, the predicted and measured TP concentrations matched if about a third of the potential anthropogenic load reached the lake. This suggests that the thick till/soil is effective in removal of some of the TP from the tile drainage, although the duration that TP removal will continue is unknown.

On the other hand, these thick till/soil conditions are not typical of catchments on the Precambrian Shield, and even lakes in this type of catchment are adversely affected by shoreline development. It is therefore appropriate to make the conservative assumption that shoreline development contributes its total potential anthropogenic TP load to Precambrian lakes when assessing the impact of development on such lakes.

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Table 1. The number of cottages on the shoreline of the study lakes (N) and the preliminary estimate of the potential contribution of shoreline development to the estimated TP load to the lake, expressed as the ratio of the potential anthropogenic TP load (L_A) to the potential total load (L_T = L_A + natural load).

Lake	N	L_A/L_T
Jerry	0	0
Red Chalk	3	0.04
Blue Chalk	11	0.27
Chub	11	0.26
Dickie	125	0.54
Harp	83	0.61

Table 2. Physical and chemical characteristics of the study lakes and their catchments.

Lake	A_o (ha)	$\bar{z}$ (m)	z_{max} (m)	Cond (μS/cm)	Cations (μeq/L)	Anions (μeq/L)	Colour (Hazen)	Surficial Deposits
Jerry	50.1	12.4	35	38.3	260	173	5.3	thick till
Red Chalk	57.1	14.2	38	29.5	237	216	11.3	thin till
Blue Chalk	52.4	8.5	23	29.1	238	220	6.5	thin till
Chub	34.4	8.9	27	28.3	215	184	47.7	thin till
Dickie	93.6	5.0	12	29.0	231	195	47.6	thin till
Harp	71.4	13.3	38	34.8	288	252	20.4	thick till

Table 3. Mean differences in annual hydrologic balances for the study lakes where % difference = (total outflow - total inflow)/ total outflow x 100. n is the number of years of study.

Lake	**n**		**Difference** **mean**	**Difference** **mean of absolute**
Jerry	3		+ 1.1	6.7
Red Chalk	12		+ 3.0	3.6
Chub	12		+ 2.3	5.9
Blue Chalk	12		+ 5.1	5.9
Dickie	12		+ 0.8	3.2
Harp	12		- 2.8	4.2
		Mean	**2.7**	**4.6**

Table 4. The total loading of TP (L_T) from external (L_{EXT}), internal (L_{INT}), natural ($L_{NAT} = L_{EXT} + L_{INT}$) and anthropogenic ($L_A$) sources ($mg/m^2/yr$), the measured areal water load (q_s in m/yr), the predicted fractional retention of TP (R_p) and the measured ($[TP]_{meas}$) and predicted total phosphorus concentration during the ice-free season (mg/m^3) from natural only ($[TP]^{NAT}_{pred}$) or all TP inputs ($[TP]^{T}_{pred}$) for the undeveloped lakes. All data are averages for 12 years (Red Chalk) or 3 years (Jerry). The values reported for Red Chalk Lake are volume-weighted averages of the data collected for each basin.

Lake	Jerry	Red Chalk
L_{EXT}	184	72.0
L_{INT}	5	3.3
L_{NAT}	189	75.3
L_A	0	1.1
L_T	189	76.4
L_A/L_T (%)	0	1.4
q_s	10.0	5.82
R_p	0.56	0.66
$[TP]^{NAT}_{pred}$	8.7	4.60
$[TP]^{T}_{pred}$	8.7	4.66
$[TP]_{meas}$	8.6	5.1

Table 5. The total loading of TP (L_T), the measured areal water load (q_s in m/yr), the fractional retention of TP (R_p) and the measured ($[TP]_{meas}$) and predicted ($[TP]_{pred}$) total phosphorus concentration during the ice-free season (mg/m^3) in each basin of Red Chalk Lake. Values are 12 year averages.

Parameter	**Main basin**	**East Basin**
L_T (mg/m^2/yr)	87	175
q_s (m/yr)	7.53	16.1
R_p (/yr)	0.43	0.31
$[TP]_{pred}$ (mg/m^3)	4.6	7.9
$[TP]_{meas}$ (mg/m^3)	4.9	7.8

Table 6. The total loading of TP (L_T) from external (L_{EXT}), internal (L_{INT}), natural ($L_{NAT} = L_{EXT} + L_{INT}$) and anthropogenic ($L_A$) sources ($mg/m^2/yr$), the measured areal water load (q_s in m/yr), the predicted fractional retention of TP (R_p) and the measured ($[TP]_{meas}$) and predicted total phosphorus concentration during the ice-free season (mg/m^3) from natural only ($[TP]^{NAT}_{pred}$) or all TP inputs ($[TP]^{T}_{pred}$) for the moderately developed lakes. All data are averages for 12 years.

Lake	Blue Chalk	Chub
L_{EXT}	32.5	84.0
L_{INT}	5.6	26.2
L_{NAT}	38.1	110.2
L_A	11.6	15.7
L_T	49.7	125.9
L_A/L_T (%)	23.3	12.4
q_s	1.61	4.45
R_p	0.82	0.62
$[TP]^{NAT}_{pred}$	4.5	9.8
$[TP]^{T}_{pred}$	5.8	11.2
$[TP]_{meas}$	6.4	10.5

Table 7. The total loading of TP (L_T) from external (L_{EXT}), internal (L_{INT}), natural ($L_{NAT} = L_{EXT} + L_{INT}$) and anthropogenic ($L_A$) sources ($mg/m^2/yr$), the measured areal water load (q_s in m/yr), the predicted fractional retention of TP (R_p) and the measured ($[TP]_{meas}$) and predicted ($[TP]_{pred}$) total phosphorus concentration during the ice-free season (mg/m^3) from natural only ($[TP]^{NAT}_{pred}$) or all TP inputs ($[TP]^{T}_{pred}$) in the extensively developed lakes. All data are averages for 12 years.

Lake	Dickie	Harp
L_{EXT}	82.2	83.2
L_{INT}	5.3	3.0
L_{NAT}	87.5	86.2
L_A	86.2	116.8
L_T	173.7	203.0
L_A/L_T (%)	49.6	57.5
q_s	2.82	4.33
R_p	0.82	0.74
$[TP]^{NAT}_{pred}$	5.8	5.4
$[TP]^{T}_{pred}$	11.6	12.8
$[TP]_{meas}$	11.7	7.5